

# Shedding Light on Dark Matter

**T**HE “stuff” that makes up the universe is mostly invisible. Matter that we can see or detect, such as the substances that make up the planets, stars, and interstellar dust, comprises only 4 percent of the total. The rest of the mass in the universe, most scientists believe, consists of dark matter—matter of unknown composition that does not emit or reflect electromagnetic radiation and is therefore difficult to observe directly. Determining the nature of this “missing mass” is one of the most important problems in modern cosmology and particle physics. Several kinds of particles have been proposed as dark-matter candidates, and many experiments and searches are under way to detect them. One candidate is some kind of a weakly interacting massive particle (WIMP). Because WIMPs do not interact with electromagnetism or interact strongly with matter, they are nearly impossible to detect directly.

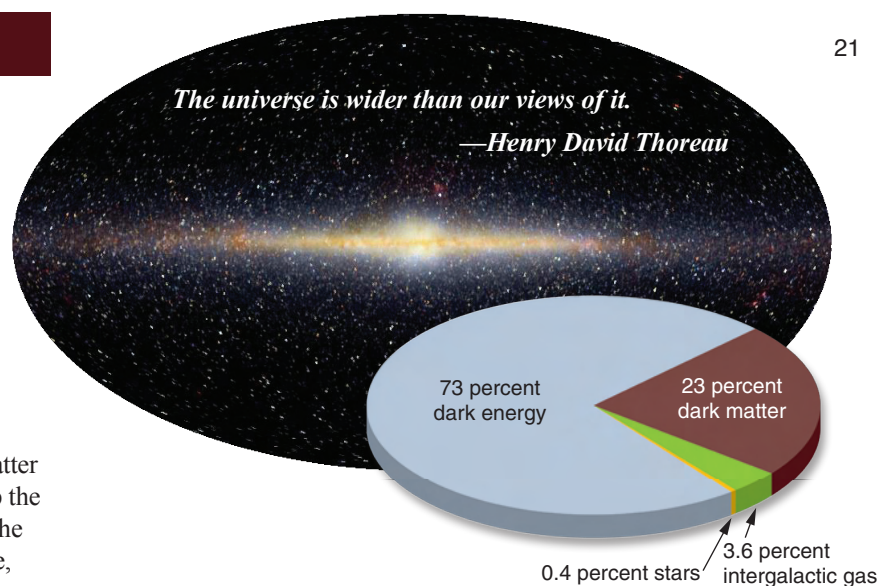
At Lawrence Livermore, physicist William Craig is the principal investigator of an effort to indirectly detect dark-matter WIMPs in cosmic rays by looking for the antiparticles the WIMPs produce when they interact with each other. To this end, Craig, his team of researchers from Livermore, and researchers at Columbia University have developed a novel general antiparticle spectrometer (GAPS) to shed light on the possible constituents of dark matter in the universe.

## Antiparticles, Unite!

Dark matter has been detected by its gravitational lensing of distant galaxies, in which unseen matter “magnifies” galaxies behind it. Theory points to a concentration of dark matter in the middle of the Milky Way Galaxy. Still, determining exactly what constitutes this dark matter is not easy.

A leading candidate for dark matter is a hypothetical particle called the neutralino. The neutralino—a stable, heavy WIMP predicted by some models in particle physics—has properties similar to those of neutrinos and is similarly difficult to detect. Efforts are under way by other researchers to detect the neutralino by looking for the recoil experienced by a target atom when a neutralino hits it. Unfortunately, the recoil from a neutralino cannot be distinguished from the recoil produced by a neutron. Therefore, these recoil experiments must be conducted deep underground and shielded as much as possible from the neutrons produced by cosmic-ray reactions and natural radioactivity.

Another way to chase down the neutralino involves indirect detection—this method is the path that Craig and his team



Only about 4 percent of the matter in the universe is composed of visible substances. The balance is dark matter and dark energy, although the exact compositions of dark matter and dark energy are yet to be determined. Researchers have proposed several kinds of particles as dark-matter candidates, including a weakly interacting massive particle. (Image of Milky Way Galaxy courtesy of the National Aeronautics and Space Administration.)

have taken with GAPS. In their experiments, the focus is not on detecting the neutralino itself, but on identifying the unique “fingerprint” produced when one neutralino hits another. During the annihilation of the neutralinos, a bevy of particles and antiparticles is produced, including antiprotons and antineutrons. These two antiparticles—antiprotons and antineutrons—combine to form antideuterons. Antiparticles have the same mass but opposite charge from their particle cousins. For example, a proton has a positive charge, while an antiproton has a negative charge.

If neutralinos are indeed a major component of dark matter, then these antideuterons should be found in the cosmic rays originating from the galactic center of the Milky Way. “According to theory and calculations,” says Craig, “the flux of antideuterons from dark-matter neutralino annihilation is large enough that our GAPS technique, when used in a modest space-based experiment, should not have any trouble detecting it.”

However, these neutralino-produced antideuterons are not the only particles in the cosmic rays that shower Earth. “Secondary” antideuterons result from other cosmic-ray interactions. These secondary antideuterons tend to have a higher kinetic energy than the “primary” antideuterons produced by the dark-matter neutralinos. “So if we search for the primary antideuterons at low enough energies,” says Craig, “we don’t have to worry about contamination from the secondary antideuterons.”

GAPS could also be used for detecting other antiparticles such as antiprotons. Because antiprotons are another primary product of neutralino annihilation, their detection could help bolster the argument for neutralinos comprising dark matter. “Theory and

models indicate that the antiprotons produced in these annihilations dominate at energies below 100 megaelectronvolts,” says Craig. “Any antiprotons detected below this energy threshold are probably from neutralino collisions.”

### Covering the Energy GAPS

Detecting antiparticles requires extremely reliable identification amid enormous quantities of other particles. For instance, the antiproton flux is about  $10^5$  times lower than the proton flux, while approximately one antideuteron might be observed for every  $10^9$  protons and  $10^5$  deuterons. An antiparticle spectrometer must distinguish the types and energies of particles. The GAPS system does so with elegant simplicity, in a lightweight and straightforward package. GAPS consists of a time-of-flight system, an energy degrader, and a chamber filled with a target gas or solid. The chamber is surrounded by spectrometers.

The time-of-flight system measures the velocity of an incoming particle. The particle then enters an energy-degrading block made of a material, such as lead, that slows the particle. The degrader’s thickness is chosen so that it will slow down antiparticles of a specific type and energy by a specific amount of time. The slowed antiparticle enters the chamber, where it bumps into an atom of the target material, knocking out and replacing an electron in the atom’s outer electron shell. However, the antiparticle is much more massive than the ejected electron it replaces—for instance, an antiproton is about 1,800 times heavier than an electron. As a result, the atom—called an “exotic” atom—is unstable, and the antiparticle in the atom’s outer orbit is in a highly excited energy state. The captured antiparticle emits x-ray photons with discrete energies of 25 to 250 kiloelectronvolts as it decays from energy level to energy level, displacing bound electrons as it goes. Finally, the antiparticle decays directly into the nucleus, annihilating itself and emitting a shower of pions in the process.

The emission of x rays and pions takes just a few nanoseconds. In fact, the total time is about 7 nanoseconds from when the particle enters the time-of-flight system to when it is annihilated. Segmented x-ray spectrometers surround the target chamber on all sides except for the one the particles enter through the time-of-flight system. These spectrometers measure and record the energy levels of the emitted x rays and the pion shower.

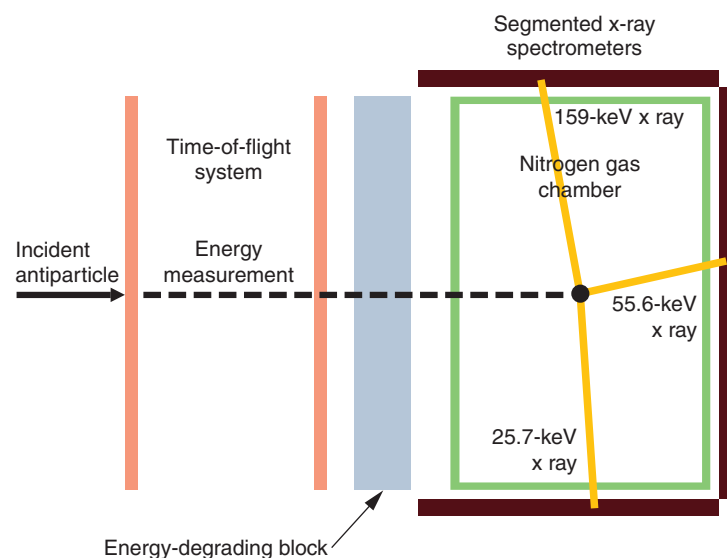
The energies of x rays and pions differ for each type of antiparticle, providing a fingerprint for particle identification. “For instance,” says Craig, “when a captured antiproton decays in an atom of nitrogen gas, it will emit, nearly simultaneously, three well-defined hard x rays of 159, 55.6, and 25.7 kiloelectronvolts. This set of signals, when detected in the presence of emitted pions, provides a clear fingerprint of a primary antiproton that originated from a neutralino annihilation.”

GAPS can easily separate cosmic antiparticles from those produced by the solar system. “We designed the x-ray detectors to

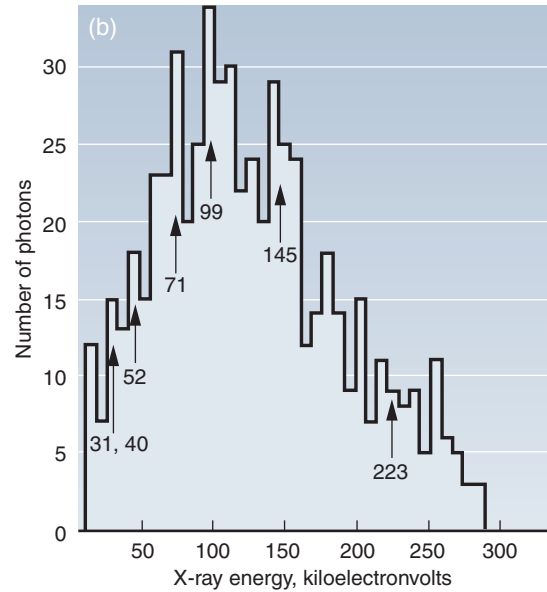
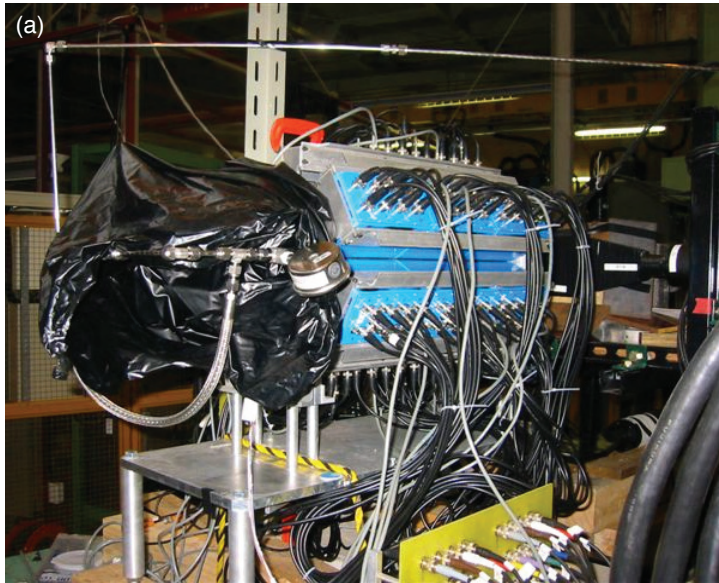
be sensitive to a narrow energy band and time window,” explains Craig. “The time-of-flight system records when an antiparticle of interest enters the system and its velocity. We can then observe the distinctive fingerprint of x rays and pions to determine if this antiparticle is the one we are seeking. We expect one antideuteron for every  $10^9$  protons. GAPS allows us to search for antideuterons, for the first time, in a definitive manner.”

### Space—the Final Frontier

Livermore’s Laboratory Directed Research and Development (LDRD) Program funded the initial work on GAPS. As part of their LDRD project, Craig and his team completed a proof-of-concept prototype and tested it at the KEK Accelerator Test Facility in Japan. They looked for antiprotons resulting from the interaction of KEK’s antiproton beam with the GAPS target material. High-quality antiparticle events were detected from four different targets. The experiment proved that GAPS could detect a specific type of antiparticle and energy amid a high flux of other particles. “The KEK tests also showed us that we could obtain good results using solid and liquid targets,” says Craig, “which greatly simplifies our design challenges. The original design used high-pressure gas as the target, which meant we had the ‘dead



The General Antiparticle Spectrometer (GAPS) developed at Livermore can capture and identify a single antiparticle in a large flux of other particles. GAPS consists of a time-of-flight system to determine the energy of incoming antiparticles, a degrader to slow down antiparticles of interest in a specific amount of time, and a chamber filled with a target liquid or solid to “capture” the antiparticle. The captured antiparticle gives off x rays of specific energies (measured in kiloelectronvolts, keV) as it decays, and the x-ray energies are recorded by surrounding spectrometers.



(a) A proof-of-concept GAPS system was tested at Japan's KEK particle accelerator. The system successfully recorded unique x-ray "fingerprints" of antiprotons using a variety of solid, liquid, and gas targets. (b) An x-ray spectrum shows the decay of captured antiprotons in the solid carbon tetrabromide target material with peaks at the expected frequencies.

weight' of a gas-handling system. With liquid or solid targets, GAPS not only weighs less but also is easier to operate and more efficient and sensitive."

In a multinational collaboration that includes groups from several institutions in the U.S. and Japan, a high-altitude balloon test in Antarctica will bring GAPS closer to space. The 20-day experiment will gather more data with more detectors—20,000 detectors versus the 128 on the prototype. Because most galactic cosmic rays have energies too low to penetrate Earth's atmosphere, this balloon test will be the first opportunity for GAPS to detect a sizable number of antideuterons. "We might detect about a dozen antideuterons," says Craig. "We'll detect thousands of antiprotons, which will allow us to do some interesting cosmic-ray physics." The experiment is scheduled in the 2010–2011 time frame.

The team's ultimate goal is to use GAPS on a space-based experiment. According to Craig, the National Aeronautics and Space Administration has expressed interest in the project. "We take our work one step at a time. This experiment is not an easy one to build," says Craig. "Still, we're excited that the answer to the big question 'what is the universe made of?' may be within our grasp."

—Ann Parker

**Key Words:** antideuteron, antimatter, antiparticle, antiproton, cosmology, dark matter, general antiparticle spectrometer (GAPS), Milky Way Galaxy, neutralino, particle physics, weakly interacting massive particle (WIMP), x-ray detector.

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